MECHANIZED EXCAVABILITY RATING FOR HARD-ROCK MINING

By Z. T. Bieniawski, D.Sc. (Eng),[1] and Benjamín Celada, Ph.D.[2]

> When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.
>
> *—Lord Kelvin (1824–1907)*

ABSTRACT

After emphasizing the importance of quantitative rock mass classifications in mining, originally directed to selection of rock support measures, but subsequently to estimates of rock mass properties such as rock mass strength and rock mass modulus of deformation, current attention calls for a classification specifically for rock mass excavability by tunnel boring machines (TBMs), which are used extensively in tunneling as well as in the mining industry.

This paper introduces the Rock Mass Excavability (RME) index for predicting excavability of rock masses by TBMs using a quantification of machine performance and rock mass conditions. The RME index is based on five input parameters aimed at relating rock mass behavior and machine characteristics: (1) uniaxial compressive strength of the rock material, (2) drillability/abrasivity, (3) rock mass jointing at mine drift face, (4) standup time of the excavation, and (5) groundwater inflow.

Development of the RME index entailed the collection of extensive data from more than 28 km of tunnels and some 400 case records from projects in Spain involving double-shield TBMs. In the process, a number of statistical correlations have been established between RME and such output parameters as degree of machine utilization, advance and penetration rates, thrust and torque of the cutterhead, and the specific energy of excavation. It was found that the RME index provides a particularly significant correlation for predicting the average rate of advance (m/day).

In essence, the RME index is a classification system that features interaction of rock mass conditions with boring machine characteristics for use in the early stages of a project.

It should be noted that the RME index does not replace the Rock Mass Rating (RMR) or Q-systems as used in mining and tunneling; indeed, one of the RME input parameters, standup time, is determined from the RMR. However, the approach presented introduces a specialized tool relevant to excavating tunnels and drifts. Possible applications to hard-rock mining are explored.

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INTRODUCTION

Rock mass classifications, although originally developed for rock tunneling in civil engineering, have been used in mining for some 35 years, going back to RMR applications in South African hard-rock and coal mining [Bieniawski 1972; Laubscher 1976]. In the United States, research investigations by Kendorski et al. [1983] for hard-rock mining, based on RMR, as well as for coal mining by Unal [1983] for roof support and Kalamaras and Bieniawski [1995] for pillar design, also based on RMR, were highly innovative, and their results are used to this day.

More recently, attention has been paid to rock mass classifications aimed at determining rock mass properties, i.e., rock mass strength and the rock mass modulus of deformation. Examples of particularly useful charts for this purpose are presented in Appendix B of this paper.

Lately, as machine-bored excavations in tunneling become more common than drill-and-blast tunneling, a need emerged for predicting the performance of tunnel boring machines (TBMs) based on considerations of interaction of rock mass conditions and the TBM operational parameters. If successful, such findings would be of equal interest to mining applications.

PREVIOUS STUDIES

When one considers the history of underground excavation technology, its development, and the major milestones, the emergence and increasing use of modern TBMs provided both spectacular advantages and achievements, as well as complex challenges and problems to designers and constructors who faced significant shortcomings in our understanding of the interaction of rock mass conditions and TBM design and performance.

In fact, when Terzaghi introduced his rock load concept in 1946, followed by Lauffer's standup time concept in 1958 and Deere's Rock Quality Designation (RQD) in 1964, these design approaches were directed to selection of rock reinforcement for tunnel construction by drilling and blasting. The equipment selected for tunnel excavation was left to the discretion of the contractor, with little input by the designer. Even subsequent modern rock mass classification methods [Bieniawski 1973; Barton 1974] were predominantly directed to drill-and-blast tunnels, independent of TBM characteristics.

Today, this is no longer the case. TBMs have increased in power, size, and type to such an extent that they directly influence tunnel design. Moreover, their selection is a source of tremendous satisfaction due to increased safety and higher performance, as well as deep despair when unexpected ground conditions are encountered and the TBM may be immobilized for months and sometimes has to be rescued by old-fashioned hand mining or conventional drill-and-blast excavation.

A major problem emerged: how to assess effectively the interaction between rock mass conditions, as described by the RMR or Q classification systems, and the design and performance characteristics of the TBM. Certainly, some attempts to solve this problem have been made, as reviewed below, but the state of the art still rests on the TBM manufacturers and tunnel contractors that must rely on their experience, ingenuity, and even the will to survive many adverse conditions.

STATE OF THE ART IN ROCK EXCAVABILITY

Excavability is defined as the ease of excavation and was investigated as early as Kirsten [1982]. TBM excavability or performance prediction models were studied by Barton [2000], Alber [2001], Bieniawski [2004], Blindheim [2005], and others.

In essence, it is recognized that the choice between a TBM and drilling and blasting can be quantified based on rock mass quality and machine characteristics. An example of an interdependence function is the Q_{TBM} formulation [Barton 2000]:

$$Q_{TBM} = RQD_0/J_n \times J_r/J_a \times J_w/SRF \times \sigma_{MASS}/F \times 20/CLI \times q/20 \quad (1)$$

where CLI = cutter life index (Norwegian Institute of Technology), SRF = stress reduction factor, F = average cutter load (tnf), q = quartz content (%).

Equation 1 received much attention, but was also severely criticized [Blindheim 2005]. In this research, the above relationship was also tested, but without success because of the problem with the definition of rock mass strength, σ_{MASS}, which is based on "inversion of σ_c to a rock mass strength, with correction for density," rendering it unacceptable. Nevertheless, Abrahão and Barton [2003] applied this equation with all 21 parameters ("for which no apology is made," declared the authors), emphasizing that the rock-machine interaction in tunneling is very complex.

Subsequently, the key objection to Q_{TBM} was provided by a major study from Norway (where the Q-system was invented) published by Palmström and Broch [2006]. They concluded:

> Q_{TBM} is complex and even misleading and shows low sensitivity to penetration rate; the correlation coefficient with recorded data is even worse than conventional Q or RMR or with other basic parameters like the uniaxial compressive strength of the intact rock. It is recommended that the Q_{TBM} should not to be used.

This finding is clearly supported by Figure 1.

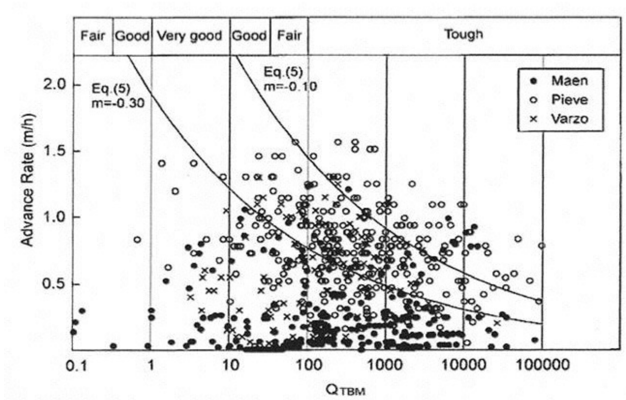

Figure 1.—Advance rates for three TBM tunnels plotted against Q_{TBM} [Sapigni et al. 2002].

Other attempts were reported by Alber [2001] concentrating on contracting practice and probabilistic estimates of advance rates and project economics. The RMR system was used by Grandori et al. [1995] to demonstrate ranges of effectiveness for TBM performance in different rock mass quality as a function of machine type: open TBM or double-shield. Bieniawski [2004] reviewed the concept of rock mass excavability based on the RMR as adjusted for TBMs.

However, there is convincing evidence that complex equations combining rock mass quality RMR or Q with additional parameters related to TBM characteristics are not an effective approach. In other words, it is doubtful that one formula can include all the factors pertinent to rock mass quality, as well as those influencing TBM choice and performance.

In fact, expert opinion holds that the RMR and Q-systems are most effective as they are commonly used, consistent with the purposes for which they were developed. Thus, adjusting these systems for TBM-sensitive parameters, such as rock abrasivity and cutter thrust, may be counterproductive and may only create confusion.

THE CONCEPT OF THE ROCK MASS EXCAVABILITY (RME) INDEX

After much overwhelming evidence, such as shown in Figure 1, we concluded that modifying an existing rock mass quality classification, be it the RMR or Q, for determining rock mass excavability was not an effective approach for modern engineering practice. Accordingly, research devoted to rock mass excavability was initiated in 2004 with the objective of establishing an index, similar to the RMR, but which was specifically directed to predicting rock mass excavability, rather than rock mass quality. This work was aimed at selecting the appropriate method of tunnel excavation, having considered rock mass-machine interaction, using TBMs or conventional mechanized excavation. The RME concept proposed first by Bieniawski et al. [2006] was based on analyses of 387 sections of three Spanish tunnels comprising 22.9 km in length. In each case, the tunnels studied included detailed data on rock mass characteristics and TBM parameters, as shown in the RME input data form in Figure 2.

INPUT DATA FORM for Rock Mass Excavability

Name of Tunnel ....

Initial chainage of section:..............................Final chainage of section..

Length of section:..............................m (should be > 40 m)

Duration of excavation (days):... (number + 1 decimal)

Average Rate of Advance ARA = ...m/day

Lithology:...Average depth:............. ....m

ROCK MASS PARAMETERS

Uniaxial compressive strength of intact rock (?$_c$):..MPa

Drilling Rate Index DRI:................. Type of homogeneity at excavation face:..................... ....

N° of joints per meter:...............Rock Mass Rating *RMR*: range.........................average.............

Orientation of discontinuities with respect to tunnel axis

(perpendicular, parallel or oblique):...

Stand up time:...................hours Groundwater inflow at tunnel face: ....liters/sec

Rock Mass Excavability RME range....................................average...................

TBM PARAMETERS

Average speed of cutterhead rotation: ....rpm Applied Thrust:...................m . kN

Specific Penetration:.....................................mm /rev

Rate of Penetration:...................................... mm /min

N° cutters changed:....................................... Rate of TBM utilization: ....%

Figure 2.—Input data form for determining the Rock Mass Excavability (RME) index.

Table 1.—Input ratings for Rock Mass Excavability (RME) index

UCS OF INTACT ROCK (0–25 points)

σ_c (MPa)....................	<5	5–30	30–90	90–180	>180
Average rating	4	14	25	14	0

DRILLABILITY (0–15 points)

Drilling Rate Index	>80	80–65	65–50	50–40	<40
Average rating	15	10	7	3	0

DISCONTINUITIES AT TUNNEL FACE (0–30 points)

	Homogeneity		Number of joints per meter					Orientation with respect to tunnel axis		
	Homo-geneous	Mixed	0–4	4–8	8–15	15–30	>30	Perpendicular	Oblique	Parallel
Avg. rating	10	0	2	7	15	10	0	5	3	0

STANDUP TIME (0–25 points)

Hours	<5	5–24	24–96	96–192	>192
Average rating	0	2	10	15	25

GROUNDWATER INFLOW (0–5 points)

L/sec	>100	70–100	30–70	10–30	<10
Average rating	0	1	2	[1]4	5

[1]Zero for argillaceous rocks.

SELECTION OF RME INPUT PARAMETERS

The RME index is based on the five input parameters listed in Table 1, together with the ratings associated with each. Selecting the five parameters involved a Linear Discriminant Analysis using the R code developed by the Institute of Statistics and Probability Theory of the Vienna University of Technology, Austria. As a result of this analysis, it was found that the parameters with stronger influence in the average rate of advance (ARA), expressed in m/day, are: drillability/abrasivity, discontinuity spacing, and standup time. In addition, it was decided to include the two basic rock mechanics parameters: uniaxial compressive strength (UCS) of the rock material and water inflow because these two factors are known to strongly influence the TBM advance. Once the five parameters were selected, a weighted distribution was performed. These weights have been statistically analyzed, minimizing the error in the ARA prediction and resulting in the ratings shown in Table 1.

In practice, four of the input parameters are determined from standard site exploration programs: UCS of the rock material, rock drillability, rock mass jointing (spacing, orientation, and condition of discontinuities at the tunnel front), and groundwater inflow. The fifth parameter, standup time, is estimated from the well-known RMR chart (Figure 3), which depicts standup time versus unsupported active span as a function of RMR (after Bieniawski [1989]; see also Appendices A and B of this paper). As the case studies on that chart were derived from drill-and-blast tunnels, a correlation obtained by Alber [1993] is used for TBM tunnels. The following equation is applicable:

$$RMR_{TBM} = 0.8 \times RMR_{D\&B} + 20 \qquad (2)$$

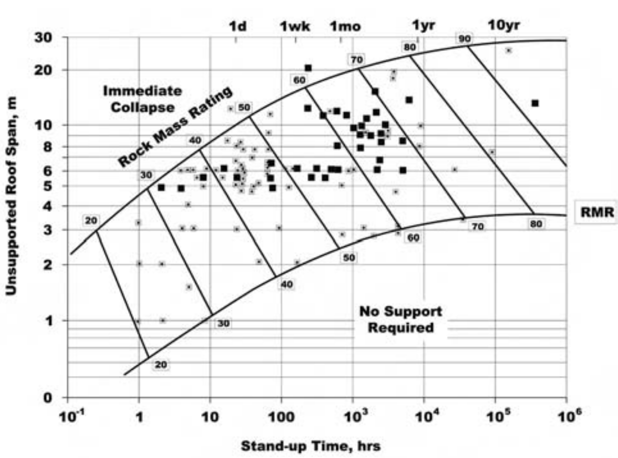

Figure 3.—Standup time as a function of RMR and unsupported span [Bieniawski 1989].

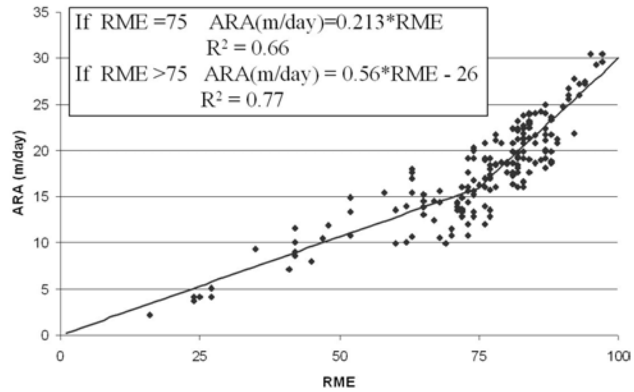

Figure 4.—Correlation between the RME index and the average rate of advance (m/day) for single- and double-shield TBMs.

CORRELATION BETWEEN AVERAGE RATE OF ADVANCE (ARA) AND RME

The average rate of advance (ARA), expressed in m/day, is the most significant parameter to compare performances from several tunnel or drift construction projects. The statistical analyses carried out provided the correlation depicted in Figure 4 between the ARA and RME for single- and double-shield TBMs.

These findings were derived for tunnels with diameters close to 10 m. In order to take into account the influence of other tunnel diameters, D, the coefficient kD is used. The values of kD can be calculated from the following expression:

$$kD = -0.007D^3 + 0.1637D^2 - 1.2859D + 4.5158 \qquad (3)$$

CORRELATIONS OF RME WITH OTHER PARAMETERS

A number of significant correlations were obtained in this study in addition to those discussed above.

Specific Energy of Excavation

The concept of specific energy of excavation (E_s) for mechanized tunneling and mining is "borrowed" from the petroleum and gas drilling industry, where it has been used for many years [Teale 1965]. Most recently, this concept was applied to assess the ease of mechanical excavation involving this expression:

$$E_s = F/A + 2\pi\ N\ T/\ A \times ARA \qquad (4)$$

where E_s = specific energy of excavation (kJ/m^3);
F = total cutterhead thrust (kN);
A = excavated face area (m^2);
N = cutterhead rotation speed (rps);
T = applied torque (kN·m);
and ARA = average rate of advance (m/s).

The above equation consists of two terms. The first represents the specific energy of the cutterhead thrust from static loading, while the second is the specific energy of rotation incurred by the rotating cutterhead. In this study, the specific energy of rotation (E_r) was related to the RME in Figure 5.

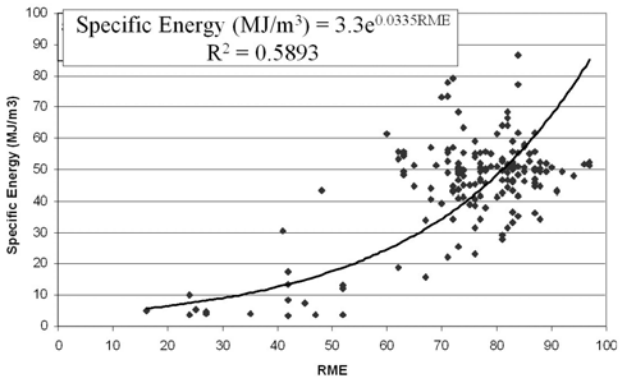

Figure 5.—Correlation between the RME index and the specific energy of excavation.

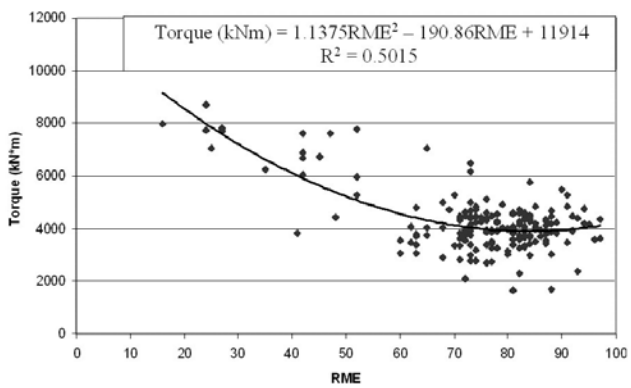

Figure 6.—Correlation between the RME index and TBM torque.

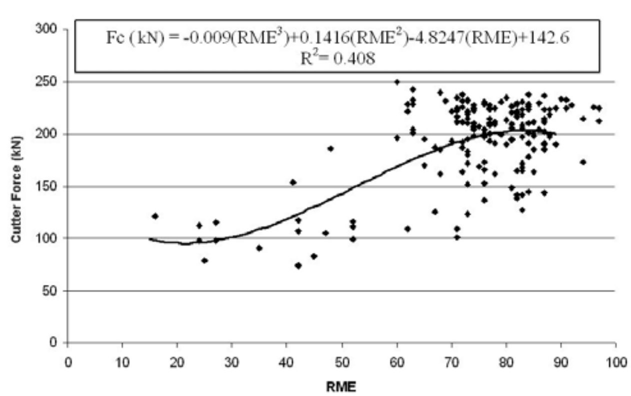

Figure 7.—Correlation between the RME index and cutterhead thrust.

Cutterhead Thrust (F_C) and Torque (T)

Figures 6–7 show the correlation of RME with both F_C and T values, providing acceptable coefficients of R=0.64 and R=0.71, respectively, for single- and double-shield TBMs.

LATEST FINDINGS

The construction of the famous Guadarrama tunnels involving two tubes, each 9.5 m in diameter and 28 km long, using four double-shield TBMs, led to the introduction of an adjustment to the predicted ARA obtained from a given RME, incorporating the effect of the length of the tunnel excavated and the influence of the crew skills when dealing with the TBM and the terrain. This can be represented as

$$ARA_T = \frac{ARA_R}{F_L \times F_C} \quad (5)$$

where ARA_T = predicted true value of ARA from the correlation with RME;

ARA_R = recorded average rate of advance, m/day, achieved in a tunnel section;

F_L = factor of experience as a function of tunnel length excavated;

and F_C = factor of effectiveness by the crew handling the TBM and the terrain.

Based on the results obtained during construction of the Guadarrama and Abdalajís Tunnels, Tables 2–3 show the values appropriate for the coefficients F_L and F_C.

Table 2.—RME adjustment factor (F_L)

Tunnel length excavated (km)	Adjustment factor (F_L)
0.5	0.50
1.0	0.86
2.0	0.97
4.0	1.00
6.0	1.07
8.0	1.12
10.0	1.15
12.0	1.20

Table 3.—RME adjustment factor (F_C)

Effectiveness of the crew handling TBM and terrain	Adjustment factor (F_C)
Less than efficient	0.88
Efficient	1.00
Very efficient	1.15

This produces a refined RME_{07} correlation depicted in Figure 8 devoted specifically to double-shield TBMs.

SPECIAL CONSIDERATIONS FOR APPLICATIONS IN MINING

Applications of rock mass classifications in mining require some special considerations compared to civil engineering for a number of reasons. The three most important are—

1. The effect of in situ stresses, since mines are usually deeper than tunnels;
2. The effect of the induced stresses, because in mining the stress field changes as mining advances and also due to adjacent excavations; and
3. The effect of blasting damage, because in hard-rock mining drilling and blasting, unless smooth blasting is used, may have an adverse effect on stability compared to machine boring.

As a matter of fact, all of the above effects were incorporated into the Mining Basic RMR (MBR) classification proposed by Kendorski et al. [1983].

There are various types of excavating machines used in mining. In modern hard-rock mines, machine excavation is used to construct access drifts and chambers, while in coal mines, continuous miners and shearers are common. In each case, to access mineral deposit production, mines employ roadheaders and/or open-type TBMs.

The RME index can be applied directly to evaluate excavability of mine drifts and chambers. However, at the time of writing, work on correlations between the RME and ARA is still in progress for roadheaders and open TBMs. In fact, investigations to determine a correlation between the RME and ARA for open-type TBMs began last year, with results expected to be presented by June 2007.

As far as applications to roadheaders and similar machines are concerned, we are still in the process of data collection and would welcome any case histories of RME applications in this respect by interested parties. In

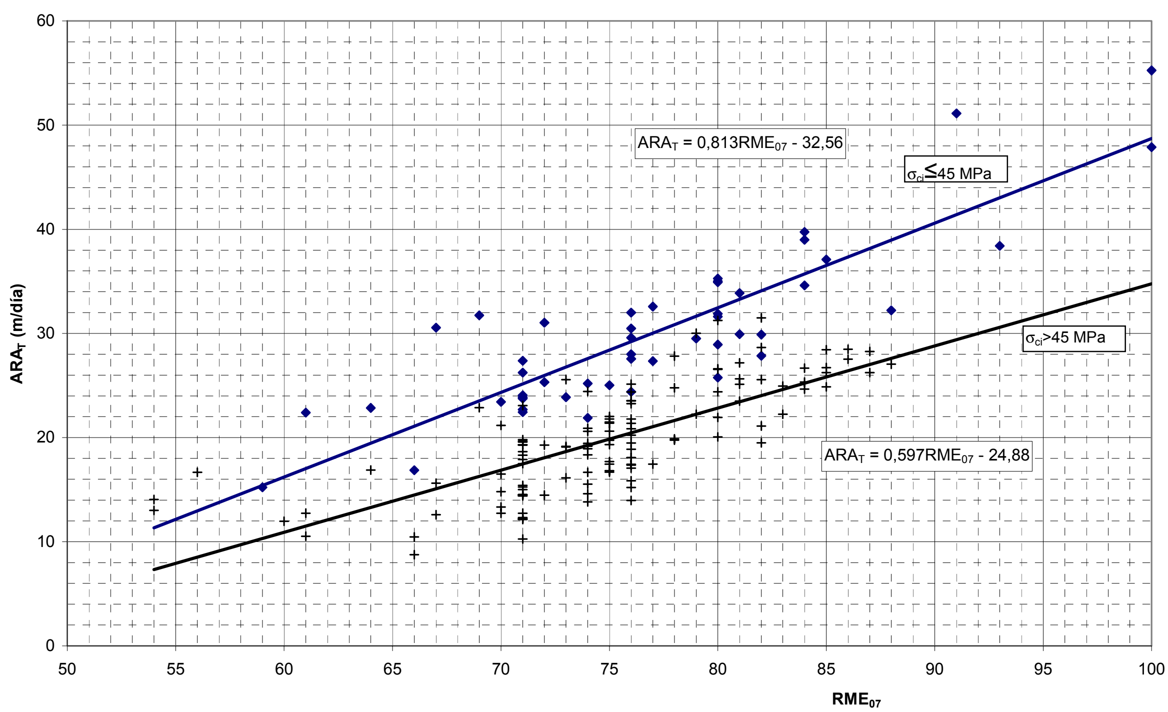

Figure 8.—Correlation between the RME_{07} and the average rate of advance for double-shield TBMs. For RME<50, TBMs in double-shield mode are not recommended.

addition, applications in room-and-pillar and longwall mining will require modifications to the actual structure of the RME index due to the specific nature of such mining operations. For example, the ratings for the standup time parameter may require an adjustment factor due to the degree of fracturing in the roof strata and due to the effect of the induced stress in order to better assess the stability of the rock mass in these types of mining operations.

CONCLUSIONS

After 3 years of studies and analyses of more than 400 case histories, RME seems to provide a tool that enables tunnel designers and constructors to estimate the performance of TBMs. Future work will focus on extending the RME to all types of TBMs and improving the existing correlations with the significant operational output parameters. Extending this work for more applications to mining provides challenging opportunities.

ACKNOWLEDGMENTS

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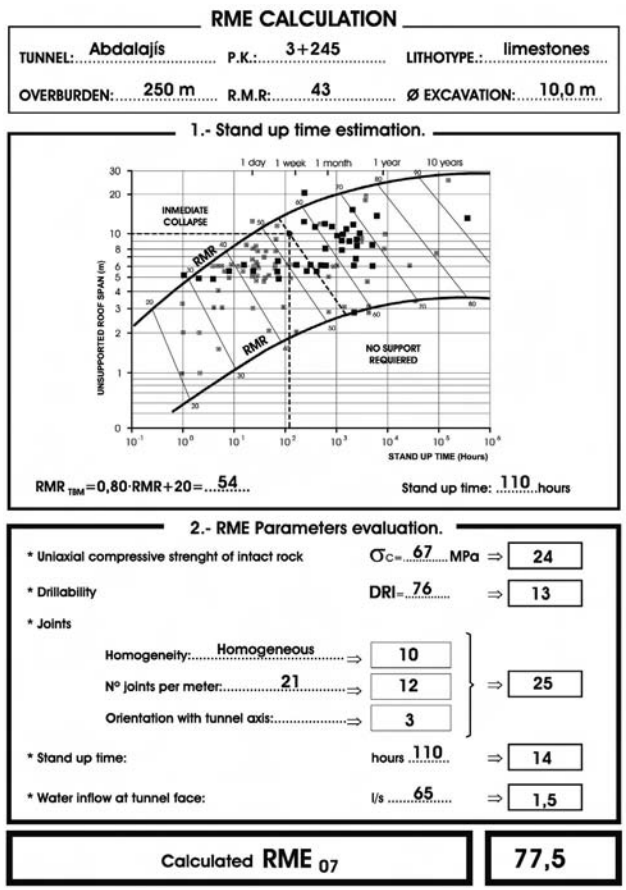
APPENDIX A.—EXAMPLE OF RME CALCULATIONS

The figure below presents an example of the actual procedure for calculating RME_{07} for one of the case histories plotted in Figure 8.



APPENDIX B.—GENERAL GUIDELINES ON ROCK MASS CLASSIFICATIONS (BASED ON THE RMR SYSTEM: 35 YEARS LATER)

The Rock Mass Excavability classification features one parameter—standup time—depicted in Figure 3, which is determined from the Rock Mass Rating (RMR), as shown in Appendix A. Since RMR was first introduced in 1972 and published internationally in 1973, it is appropriate to briefly summarize some of the lessons acquired about rock mass classifications after 35 years of use throughout the world.

The most important aspect to remember is that the main application of RMR is not just recommendations for rock support (because they change as technology changes), but estimation of rock mass properties for design and numerical purposes, i.e., the modulus of deformation of the rock mass, rock mass strength, and standup time. Figures A–1 and A–2 depict these strength and deformation relationships. In fact, the RMR case histories for these purposes still remain the prime data for analyses and correlations and are published in full [Bieniawski 1989].

There are three general guidelines to be observed for good engineering practice:

1. Rock mass classifications, either quantitative systems, such as RMR and Q, or descriptive methods (New Austrian Tunneling Method (NATM) or Geological Strength Index (GSI)), are most effective if not used on their own, but incorporated within the overall engineering design process.
2. Rock mass classifications on their own should only be used for preliminary planning purposes and not as final rock reinforcement. For preliminary design and planning purposes, the two quantitative RME and Q-systems are excellently suited. They quantify rock mass conditions, enable estimates of rock mass properties, and provide the reference bases for expected rock mass conditions.
3. The two predominant quantitative rock mass classifications, RMR and Q, are particularly essential for monitoring rock conditions during construction or mining to enable effective comparison of predicted conditions from site investigation with those encountered. For this purpose, descriptive classifications (those not based on quantitative input data) are deficient. They do not provide a continuous quantification of the encountered conditions, even if based on deformation measurements during construction, because contractual specifications in many countries prevent enough measurements to be taken since they interfere with the mining or tunneling schedule.

Most of all—users, please beware! It is not recommended to apply any rock mass classification system on its own, be it NATM, RMR, or Q. Instead, both RMR and Q should always be used to cross-check the results and compare recommendations, even if known correlations exist between these two systems, which sometimes turn out to be oversimplifications.

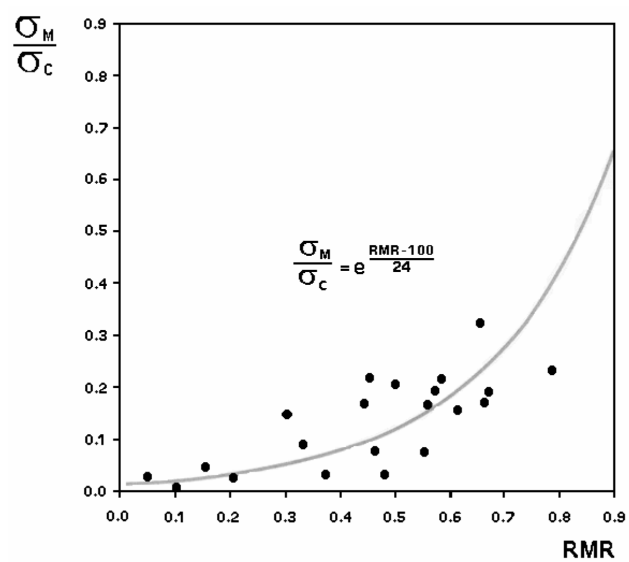


Figure A–1.—Correlation between the ratio of rock mass strength, σ_M, and UCS of rock material, σ_c, as a function of RMR [Kalamaras and Bieniawski 1995].

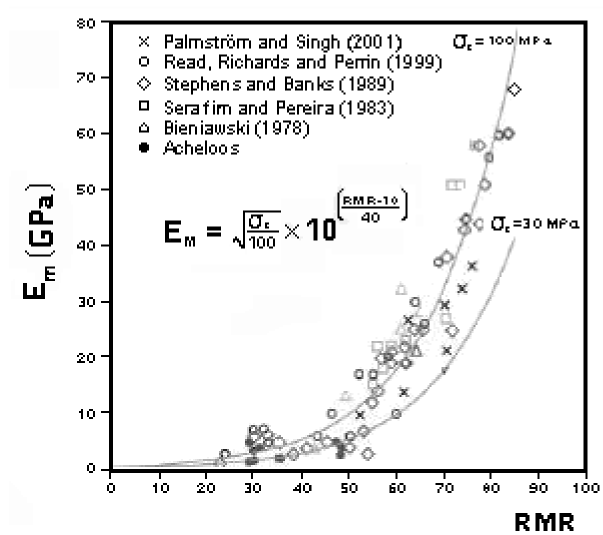


Figure A–2.—Correlation between the modulus of deformation of the rock mass, E_M, and RMR.